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TECHNIQUES FOR MEASURING ROCK WEATHERING: APPLICATION TO A DATED FAN SEGMENT SEQUENCE IN SOUTHERN TUNISIA

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ABSTRACT

There are a number of techniques for estimating the amount of weathering a clast has undergone. These usually have the objective of establishing an ordinal chronology of geomorphological surfaces, or investigation of site-specific conditions affecting weathering rates. Three such techniques are applied to a dated sequence of alluvial fan segments in southern Tunisia. Two of these techniques depend on measuring surface roughness (the micro-roughness meter and a displacement approach) and one uses the structural weakening of the rock fabric (Schmidt hammer). The micro-roughness meter enables calculation of standard deviation of surface height variation, root mean square roughness and surface autocorrelation function. Of these techniques, Schmidt hammer rebound values, standard deviation, root mean square roughness and the displacement technique show systematic changes on the three fan segments which are statistically significant at the 0.05 level. However, the amount of variance in all datasets is very large, indicating the need for caution in application of these techniques for relative dating. © 1998 John Wiley & Sons, Ltd.

KEY WORDS: rock weathering; drylands; Tunisia; alluvial fans

INTRODUCTION

Rates and modes of rock weathering are of research interest from a number of different geomorphological perspectives. Contemporary rates of weathering are important for the supply of building materials and preservation of monuments (e.g. Amoroso and Fassina, 1983; Ashton and Sereda, 1982; Trudgill *et al*., 1989; Viles, 1990). Estimates of the amount of rock weathering are often used, along with other pedological and geomorphological parameters, to determine relative ages of geomorphological surfaces (e.g. Colman, 1986; Hall and Michaud, 1988; McFadden *et al*., 1989; Whitehouse *et al*., 1986). However, research into the controls on weathering processes (see e.g. Goudie and Watson, 1984, Goudie *et al*., 1992; Jenkins and Smith, 1990; McGreevy, 1985) highlights the site-specific nature of any relationship between weathering and time; results from one environment cannot be extrapolated easily to other sites.

Much of the work on rock weathering as a chronofunction has used thickness of weathering rinds (e.g. Mills and Allison, 1995a), but the problems encountered with such approaches (Lowe and Walker, 1997) have led to some innovative developments to improve objectivity and replicability. Measurements of the velocity of compressional (P) waves through clasts have been used, based on the theory that weathering processes cause microfractures to develop in the clast, with an accompanying increase in rock compressibility (Crook, 1986; Crook and Gillespie, 1986). More recently, the measurement of Young's modulus of elasticity has shown some promise (Allison, 1990). However, the most widely applied techniques still involve the use of relatively simple equipment, such as the Schmidt hammer (McCarroll, 1989), the micro-roughness meter (McCarroll, 1990; Trudgill *et al*., 1981) and profile gauges (McCarroll and Nesje, 1996).

Despite considerable research effort, reviewed by Smith (1994), there is still much uncertainty about the relationship between rock weathering and time, lending support to calls for a more critical approach in using

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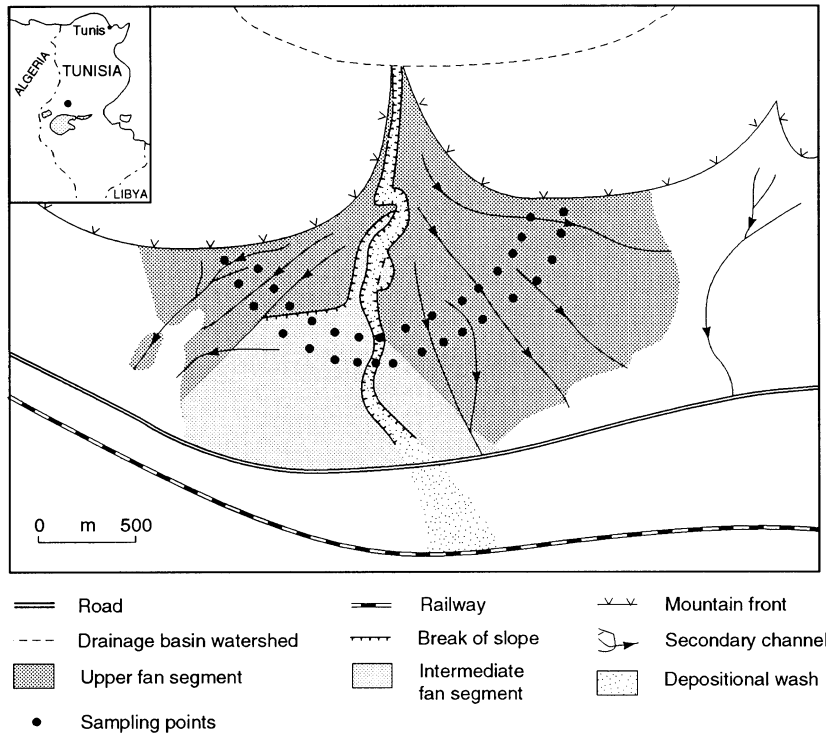
measurements of rock weathering as an indicator of relative age (McCarroll, 1991). Lowe and Walker (1997) list four problems with using rock surface weathering as an index of relative age, which we have taken into account in the design of this project.

1. *The degree of weathering is difficult to measure objectively*. This project examines this statement by comparing three approaches to the estimation of rock weathering on a dated series of three alluvial fan segments (depositional surfaces of uniform gradient formed at different stages of fan evolution) in southern Tunisia. The results should determine the ability of these techniques to provide monotonic, unambiguous indicators of relative age.
2. *Rates of weathering intensity are not linear, but decrease with age*. Even if the rates of weathering are constant (implying no significant environmental changes), the response to weathering which is being measured (e.g. surface roughness, Young's modulus etc.) is unlikely to show a linear relationship with time. Although the three alluvial fan segments provide only a present-day control and two palaeosurfaces (4468 ± 88 and $47\,000 \pm 11\,750$ years BP), our results should indicate whether the measurements of weathering employed herein are linear or non-linear over the last 50 000 years.
3. *Age calibration by radiometric methods is difficult owing to the problem of associating organic matter with specific geomorphological surfaces*. We attempt to resolve this problem by using a combination of stratigraphic ages derived from optical luminescence, and a surface age derived from AMS ^{14}C dating of a sample of organic matter found beneath a coating of rock varnish (White *et al*., 1996). However, we are still unable to assign absolute ages to individual clasts with confidence, as discussed in the following section.
4. *Weathering intensity will vary with altitude and aspect*. By concentrating on a small (644·3 ha) landform, we avoid significant altitudinal/aspect variation. Because the alluvial fan is prograding onto a salt lake, rock weathering is likely to be more intense in the more saline environment near the base. To get around this problem, we sampled all the segments at the same radial distance from the fan apex (Figure 1).

STUDY AREA

The Oued es Seffaia alluvial fan lies 13 km east of Gafsa on the south flank of Djebel Orbata in southern Tunisia (White and Walden, 1994), and covers an area of 644·3 ha (Figure 1). The drainage basin is underlain by Cretaceous carbonates, sandstones and argillites and experiences 150 mm of rainfall per annum, with peaks in the spring and autumn (Rognon, 1987). The fan has three telescopic fan segments (Figure 1), the ages of which were first determined from the distribution of Mousterian and Capsian artifacts (Coque, 1962). These ages have recently been supported by a combination of AMS radiocarbon and optical techniques (White *et al*., 1996). An upper fan segment of Mousterian age ($47\,000 \pm 11\,750$ years BP) lies above an intermediate fan segment of Capsian age (4468 ± 88 years BP), and a contemporary ephemeral depositional wash is inset within this (Table I). The telescopic segmentation of the Oued es Seffaia fan has occurred by movement of the locus of deposition away from the mountain front, and has resulted in a series of nested slope segments, successively lower segments having a lower gradient than upper segments, so that the fan segments converge distally (Blissenbach, 1954). Owing to the spatially discrete nature of deposition on alluvial fans, each segment might be expected to have significant variations in age as the locus of deposition shifted across the surface (Blair and McPherson, 1994). There are not enough extant age determinations to allow a more sophisticated analysis of the depositional chronology of the fan, thus the ages quoted above cannot be ascribed directly to all sampled points on each fan segment. A further problem is that the alluvial surfaces being studied may be relatively dynamic, in that clasts may be brought to the surface by pavement-forming processes, or may be transported from upper to lower segments by gravity. Therefore, the ages quoted above can only be taken as a rough, and possibly misleading, guide to the duration of weathering that the sampled clasts have been exposed to. The upper and intermediate segments are characterized by stone pavement cover (McFadden *et al*., 1987) providing a large number of clasts for measurement of weathering parameters. The pavement overlies a haplargid soil which shows systematic increases in concentration of pedogenic iron oxides with age (White and Walden, 1997). The depositional wash is characterized by contemporary gravelly alluvium, with no pedogenesis, and receives water and sediment in response to high intensity rainfall events on an annual basis (White, 1995).

a



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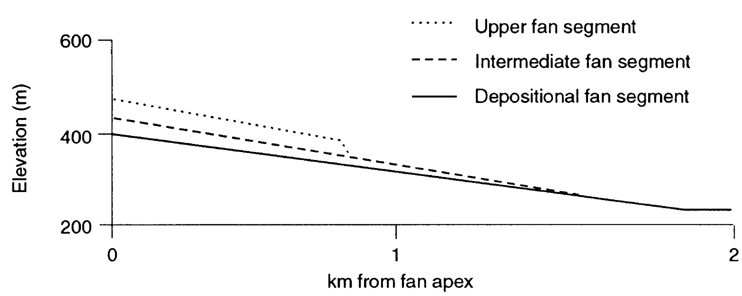


Figure 1. (a) Location map of the Oued es Seffaia, showing the location of sampling points; (b) longitudinal cross-section through the Oued es Seffaia fan, showing the relationship between the fan segments

Table I. Numerical ages of Oued es Seffaia fan segments (after White *et al.*, 1996).

Fan segment	Sediment (OSL) 25% uncertainty*	Surface (AMS ^{14}C) +/- 1σ†
Upper	47 000	–
Intermediate	8000	4468 ± 88

* The optical dates were generated from 90–125 μm quartz grains extracted by a combination of heavy liquid separation and HF etch treatments. The additive dose (multiple aliquot) method was employed using a total of 26 aliquots for each sample. Neutron activation analysis was used to estimate radioactivity levels within the sedimentary contexts. The dates presented were estimated from an equal pre-dose normalization approach and we estimate an error of 25 per cent. Performed at Oxford University, UK

† A dendrochronology-based Northern Hemisphere Terrestrial Calibration (Stuiver and Reimer, 1986) has been applied to the ^{14}C date. Performed at Institute of Geological and Nuclear Sciences, New Zealand

Figure 2. Photograph showing differences in surface roughness on clasts from the three Oued es Seffaia fan segments. The clast on the left is from the depositional wash and has been smoothed and rounded by fluvial transport. The clast in the centre is from the intermediate (Capsian) segment and has a much rougher surface. The clast on the right is from the upper (Mousterian) segment and is very rough and angular (NB the clasts have been cut to facilitate accurate determination of lithology)

Clasts sampled from the different segments on the Oued es Seffaia alluvial fan show significant differences in clast roughness (Figure 2). The clast on the left is from the depositional wash and has been smoothed and rounded by fluvial transport. The clast in the centre is from the intermediate (Capsian) segment and has a much rougher surface. The clast on the right is from the upper (Mousterian) segment and is very rough and angular (NB the clasts have been cut to facilitate accurate determination of lithology). If the assumption that clast roughness is related to length of time the clast has been exposed to subaerial weathering on the fan segment is accepted, then it is possible to use measures of clast roughness to establish an ordinal chronology of fan segments (Colman, 1986). This technique does not constitute a method of establishing age equivalence between geographically dispersed geomorphological surfaces. Lithology exerts a fundamental control on weathering and major chemical and physical differences can exist laterally within a single lithological unit, resulting in very disparate weathering characteristics (Whitehouse *et al*., 1986). Furthermore, external inputs to weathering processes, such as climatic factors and availability/type of salt, cannot be assumed to be equal over large areas (Goudie and Cooke, 1984). Clast roughness might be used to establish an ordinal chronology of segments within individual alluvial fans where all the segments develop from a similar source area, but even in this situation, the nature of the material supplied to the fan is likely to change over time as the drainage basin develops (Eckis, 1928) and this can cause problems when selecting lithologically similar clasts for measurements on different fan segments.

ROCK WEATHERING IN DRYLANDS

Dryland weathering processes are reviewed elsewhere (Goudie, 1989; Smith, 1994). Three types of weathering are of interest on carbonate lithologies (the dominant lithological group on the Oued es Seffaia fan): the first is bicarbonate dissolution, the second is biotic weathering, and the third is internal fracturing. In drylands, bicarbonate dissolution in water containing carbon dioxide is thought to be the main process, owing to the lack of organic material in the soils (Trudgill, 1985). Dissolution leads to the formation of solution pits on carbonate clast surfaces (Cooke, 1970). Dolomite solubility varies between half that of limestone to the same as limestone (Jakucs, 1977). The sources of moisture in southern Tunisia are the infrequent rainfall and more frequent mists, from which moisture condenses onto clast surfaces (Kassab and Sethom, 1980).

Danin (1983) drew attention to the importance of biologically mediated processes in dryland weathering. In Jerusalem, both cyanobacteria and the fruiting bodies of endolithic lichens have been shown to form erosion pits in limestones (Danin and Garty, 1983). Endolithic lichens are the dominant cryptogamic elements in carbonate rocks in drylands; they consist of a fungal cortex, algal layer and fungal medulla and occur at depths between 1 and 7 mm below the rock surface (Danin *et al*., 1983). Lichens are thought to promote rock weathering by both chemical (chelation) and physical (penetration by hyphae) processes (Cooks and Otto, 1990). This can be further enhanced by snails which graze on endolithic lichens (Shachak *et al*., 1987).

The third type of weathering process of interest here is that which results in internal fracturing of the rock, as this will control the coefficient of restitution and thereby the Schmidt hammer rebound values (the rebound values would also respond to differences in surface roughness owing to different degrees of direct contact made by the hammer rod on rocks of different surface roughness). In drylands the main processes thought to lead to internal fracturing of the rock are insolation weathering, freeze/thaw cycles, wetting and drying, and salt weathering (Cooke *et al*., 1993)

MEASUREMENT OF ROCK WEATHERING

A variety of techniques has been developed to measure the amount of rock weathering a clast or outcrop has undergone. This paper evaluates the use of the Schmidt hammer, micro-roughness meter, and another technique based on fluid displacement. The different techniques imposed slightly different sampling requirements, as detailed below, but two main constraints were applied throughout.

1. Clasts of the same lithology – dolomitic limestone (IIIm: micrite with microcrystalline calcite/dolomite cement of Folk, (1962)) – were used throughout to control for lithological variation.
2. Selected clasts must not show signs of human interference or of transport by agents other than fluvial action. Alluvial fans provide a ready supply of building stone and some areas contain large amounts of quarrying rubble, which were avoided.

Schmidt hammer

A Schmidt hammer (Day and Goudie, 1977; McCarroll, 1989) was used to collect a total of 480 rebound measurements, 160 on each fan segment; eight measurements were taken systematically on all aspects (N, NE, E, SE, S, SW, W, NW-facing) of 20 boulders with b-axes between 1·5 m and 1·7 m, avoiding fractured or lichen-covered patches. The same operator took all measurements to control for operator variation, and all measurements were taken in a horizontal plane. To avoid errors associated with systematic variation in instrument response (for example, changes in sensitivity resulting from progressive wear), measurements from each of the three fan segments were interspersed in a random sequence. No systematic differences of rebound with aspect were evident in these data, so a mean value for each boulder was calculated and used in subsequent analysis.

Micro-roughness meter

The surface roughness of a clast is caused by uneven weathering in response to microtopography and mineralogical variations (McCarroll, 1990) and is a function of lithology, initial fragmentation from bedrock, amount and method of transportation and the duration and intensity of subaerial weathering.

A micro-roughness meter was constructed according to the specifications of McCarroll (1990, 1992). The instrument measured micro-relief to a precision of 0·001 mm at a horizontal spacing of 1 mm along a 100 mm transect. A total of 45 sets of micro-roughness measurements were taken for this project. Fifteen boulders were selected from each of the upper segment, intermediate segment and depositional wash. A flat area was selected on the upper surface of each boulder and the micro-roughness meter was set up. Each transect consisted of 100 measurements (every 1 mm along a 100 mm transect). Although McCarroll and Nesje (1996) found that four profiles per boulder were necessary to provide representative roughness values using a carpenter's profiling gauge, this was not possible owing to the sampling requirements of the micro-roughness meter, which must be placed on a horizontal surface.

Several geometric parameters can be used to describe rock surface roughness from profile data from the micro-roughness meter; the most commonly encountered are the mean absolute difference of the adjacent surface height values, the standard deviation of differences between adjacent height values, root mean square (RMS) roughness, and the surface correlation length. All describe the statistical variation of the random component of the surface height relative to a reference surface. However, the values recorded on the profile represent differences in height between the rock and an arbitrary datum that is not necessarily parallel to the surface, so cannot themselves be used to derive a roughness index. McCarroll (1992) suggested using either the standard deviation of the difference between adjacent values (i.e. the standard deviation of the ‘slope’ values), or the mean absolute difference between adjacent ‘slope’ values in order to detrend the profile data. We adopt the standard deviation of the ‘slope’ values for this project, hereinafter termed standard deviation. Because roughness is scale-dependent, deviogram analysis (McCarroll and Nesje, 1996) was used to identify the optimum measurement interval for calculation of standard deviation. Slope values sampled across 2 mm intervals were found to give maximum separability between clasts from the three fan segments, and this sampling interval was adopted for all the standard deviation data used herein.

McCarroll and Nesje (1996) adopted the standard error of the y-estimate of a regression passing through the profile data as a measure of RMS roughness. Although sensitive to the shape of the surface over which roughness is measured, RMS roughness provides a convenient and reliable measure of surface roughness at the maximum scale present on a profile (McCarroll and Nesje, 1996).

The normalized autocorrelation function (Davis 1986) is a measure of similarity between the height z at a point x and at a point x′ distant from x. For the discrete case, the normalized autocorrelation function for a spatial displacement $x' = (j-1)\Delta x$, where j is an integer ≥1, is given by:

$$\rho(x) = \frac{\sum_{i=1}^{N+1-j} z_i z_{j+i-1}}{\sum_{i=1}^{N} z_i^2} \tag{1}$$

If $\rho(x')$ is an exponential function of distance x', then the surface correlation length l is usually defined as the distance x' for which $\rho(x')$ is equal to $1/e$ (which has a value of 0·37). The correlation length of a surface provides a reference for estimating the statistical independence of two points on the surface; if the two points are separated by a horizontal distance greater than l, then their heights may be considered to be (approximately) statistically independent of one another (Cox, 1983). In the extreme case of a perfectly smooth surface, every point on the surface is correlated with every other point with a correlation coefficient of 1. Hence $l = \infty$ in this case. Increasingly rough surfaces are expected to yield decreasing correlation lengths (Ulaby *et al.*, 1982).

The micro-roughness meter data were used to calculate standard deviation, RMS roughness and correlation length (Table II).

Table II. Mean values of the rock weathering measurements, with standard deviations in parentheses

	Depositional wash	Intermediate segment	Upper segment
Schmidt hammer rebound (mm)	47·10 (5·23) $n=20$	39·23 (7·06) $n=20$	34·54 (8·61) $n=20$
Standard deviation (mm)	0·0228 (0·0178) $n=15$	0·0278 (0·0180) $n=15$	0·0470 (0·0185) $n=15$
RMS roughness (mm)	0·0317 (0·0124) $n=15$	0·0415 (0·0118) $n=15$	0·0595 (0·0171) $n=15$
Correlation length (mm)	5·03 (3·64) $n=15$	12·79 (6·29) $n=15$	4·49 (3·40) $n=15$
Displacement (mm)	2·528 (0·90) $n=20$	8·56 (4·17) $n=20$	10·88 (4·70) $n=20$

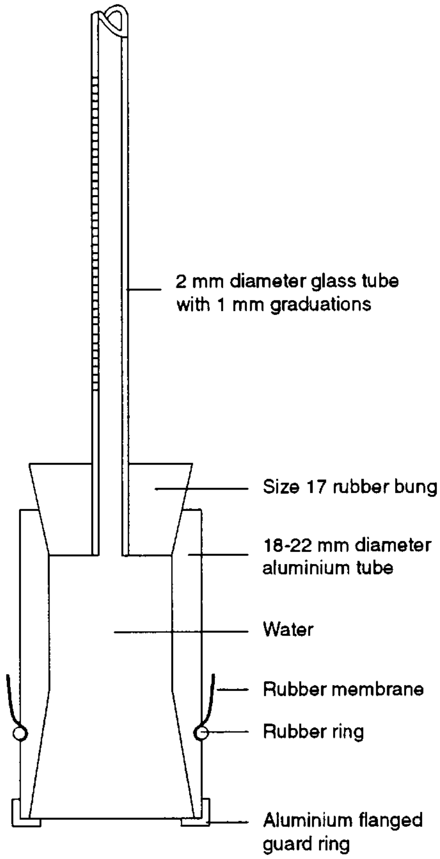


Figure 3. Schematic diagrams of the displacement meter

Displacement technique.

An alternative strategy to estimate clast surface roughness was explored by developing a simple instrument to measure the displacement of water over a rough surface, relative to a smooth reference surface. The instrument consists of an aluminium tube 50 mm long with an inside taper at the top to accept a size 17 bored rubber bung and an internal diameter at the base of 22 mm. A recess for a rubber ring is provided to seal the bottom of the tube with a rubber membrane consisting of the material used to contain soil cores in triaxial test rigs. To avoid leaks where the membrane stretched over the rim of the aluminium tube came into contact with sharp points or ridges on the clast surfaces, an aluminium guard ring was fitted. A 2 mm bore glass tube, marked with 1 mm gradations, was used to measure the displacement of liquid from the aluminium tube. Prior to use, the aluminium tube was filled with water and the measuring tube was inserted into the bung so that none protruded below the lower level of the bung, which would create air pockets inside the instrument. The bung was then pushed into the top of the aluminium tube taking care to avoid trapping air, so that the water level rises up into the measuring tube and registers a reading on the millimetre scale (Figure 3).

To make a measurement of clast roughness, the instrument is first held firmly against a smooth reference surface, in this case a piece of glazed ceramic tile, and the displacement measured on the scale (dr). A planar section of clast surface is selected and the instrument is held firmly against it, making sure it does not wobble and the base is flush with the clast surface. The displacement is measured on the scale (dt). Clast roughness is calculated from the equation:

$$R_c = d_t - d_r \tag{2}$$

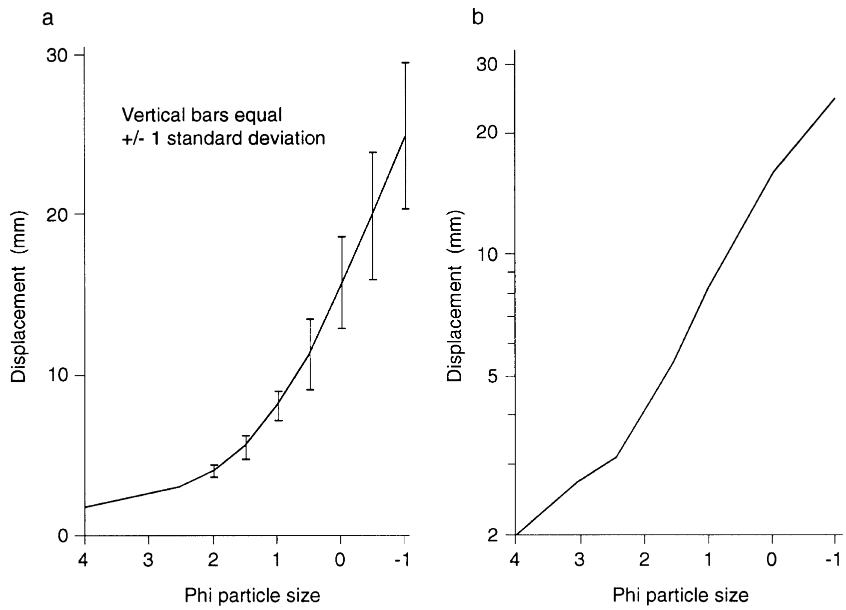


Figure 4. Calibration of the displacement meter: (a) phi particle size versus displacement (mm); (b) phi particle size versus log displacement (mm)

The sign of R_c was ignored, increasing roughness can generate both positive and negative displacement relative to the smooth reference surface, although in practice approximately 80 per cent of values of R_c were found to be positive.

In order to calibrate the displacement instrument, a series of surfaces of known roughness were constructed. This was done by sieving a sample of crushed marble through a nest of sieves of sizes phi 4, 3·5, 3, 2·5, 2, 1·5, 1, 0·5, 0, –0·5, and –1. The separated size classes were coated evenly over the sticky side of gummed labels and placed rough side up on ceramic tiles. One hundred displacement measurements were taken from each of these surfaces and the means and standard deviations were plotted against phi roughness (Figure 4a). Displacement varies from 2 mm at phi 4 to 25 mm at phi –1. The form of the relationship is curved, but this is because the phi scale is a log scale. If the graph is plotted on log-normal paper the relationship is seen to be approximately linear (Figure 4b). As roughness increases, the standard deviation of the measured displacement also increases. Between phi 4 and 2·5 the standard deviation is 0. From phi 2 to –1 the standard deviation increases from 0·4 mm to 4·5 mm. This is expected as the size of phi classes (and the range of particle sizes within each class) increases logarithmically between each interval, producing an increase in the standard deviation of displacement measurements. Nevertheless, these results suggest that displacement measurements become increasingly unreliable as roughness increases.

The main disadvantage of the displacement instrument is that the measurements are affected by the larger-scale shape of the surface being measured; if the instrument is placed over a convexity or concavity, it will register a large displacement, even if the surface of the convexity or concavity is very smooth. However, the main advantage of the displacement instrument over the micro-roughness meter is that it allows a very large number of measurements to be collected very quickly, reducing the effects of non-systematic errors such as the larger-scale shape of the surface.

Five displacement measurements were taken on each of 20 clasts on each fan segment, giving a total of 300 measurements.

RESULTS

Descriptive statistics derived from the data generated from the above techniques are summarized in Table II and plotted in Figure 5. Data were tested for normality prior to application of statistical tests.

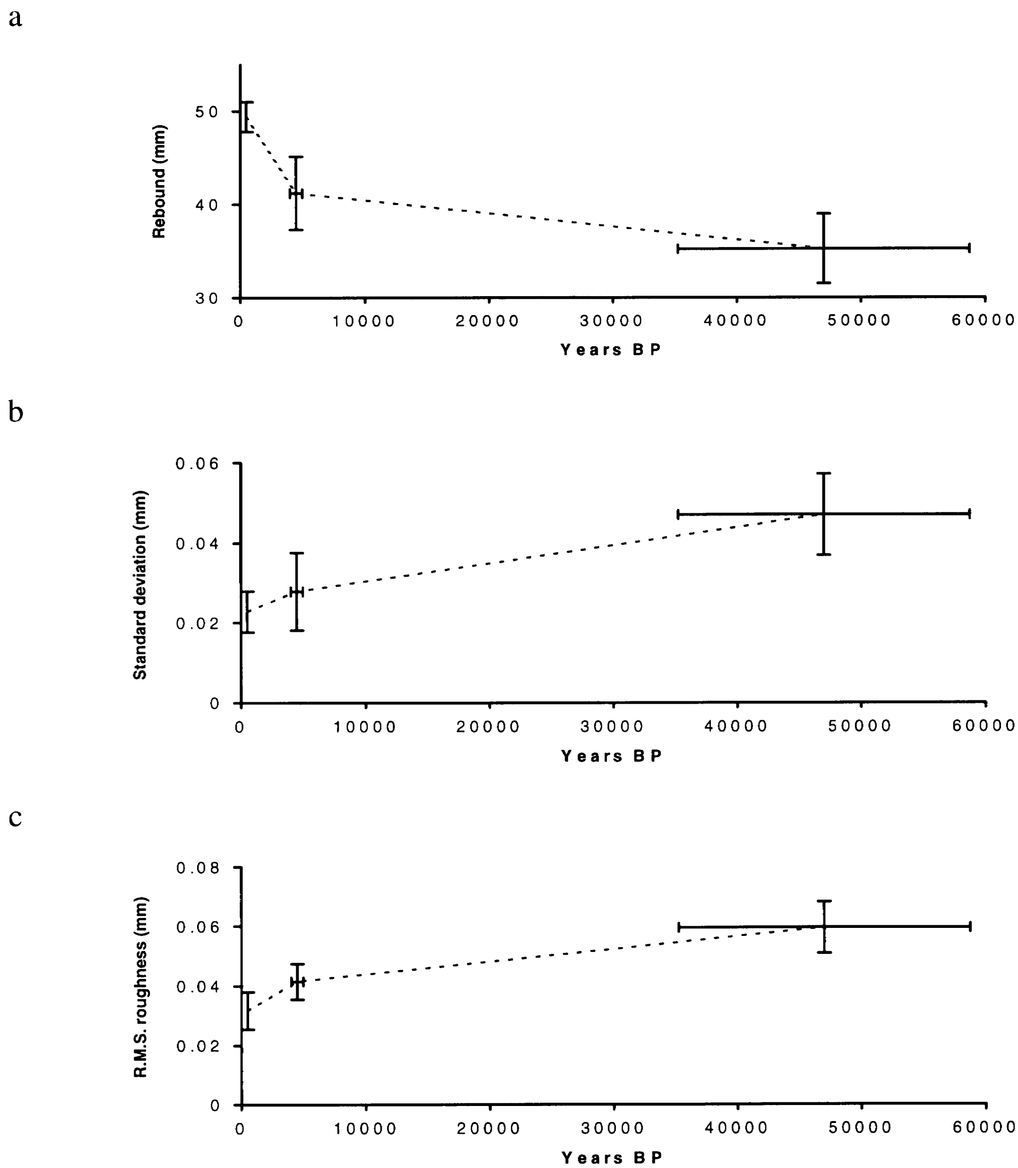
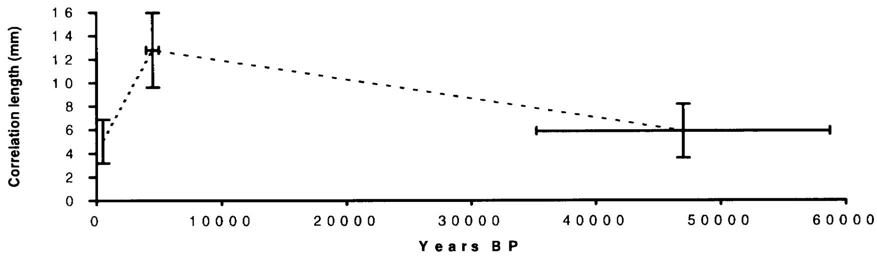


Figure 5. Estimates of rock weathering on the three Oued es Seffaia alluvial fan segments: (a) Schmidt hammer rebound data; (b) standard deviation data; (c) RMS roughness data; (d) correlation length data; (e) displacement data. X error bars = uncertainties on age (zero on the depositional wash, 88 years on the intermediate segment and 11 759 years on the upper segment); Y error bars = ±95 per cent confidence limits. Note that dotted lines linking data points are to aid interpretation only, and do not infer linearity of trend

d



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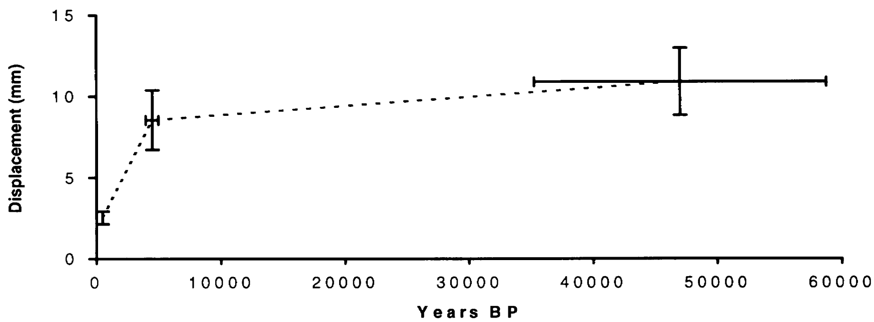

Figure 5 – continued

Schmidt hammer rebound data

The rebound data are not normally distributed, and must be analysed with a non-parametric test statistic. The Kruskal–Wallis test statistic ($H=22{\cdot}60$, $H_{crit}=5{\cdot}99$) is significant at the 0·05 significance level, showing a decrease in rebound values on older segments (Figure 5a). Rebound value data cannot be regarded as completely independent of the roughness, as McCarroll (1992) has demonstrated the importance of the surface roughness at the point of impact on controlling the amount of rebound. The smoother the clast surface roughness, the greater the rebound value owing to the greater amount of surface contact made by the hammer, all other things being equal.

Micro-roughness meter data

Both standard deviation and RMS roughness data show an increase over time (Figure 5b,c). Both sets of data deviate markedly from normality and are therefore analysed with non-parametric statistical tests. The Kruskal–Wallis test statistic ($H=12{\cdot}66$ for standard deviation data and $H=17{\cdot}54$ for RMS roughness data, $H_{crit}=5{\cdot}99$) indicates a statistically significant difference between roughness of the three fan segments at the 0·05 significance level.

The correlation length data do not show a statistically significant monotonic relationship with time (Figure 5d). The autocorrelation functions are too 'noisy' in a statistical sense and do not approximate smooth exponential functions. As a result, the point at which the autocorrelation function equals $1/e$ is inappropriate as a measure of roughness. Similar problems have been identified when using autocorrelation functions to characterize surface roughness at larger spatial scales for radar remote sensing applications (Wang *et al.*, 1986). It has been suggested that the major cause of this noise is that there are too few data points on the transect. Each transect here is defined by 100 points, and even small variations in individual points can have a dramatic effect on the calculated autocorrelation function. Longer transects, or more densely sampled transects, might improve the determination of correlation length (Archer, 1995). We conclude that correlation length, as we have

calculated it here, is not a reliable measure of clast surface roughness across the range of roughnesses encountered in this project.

Displacement meter data

The displacement data (Figure 5e) deviate markedly from normality, so must be analysed with non-parametric tests. The Kruskal–Wallis test of the displacement measurements indicates that there is a significant difference between the displacement values yielded by the three fan segments ($H=150{\cdot}73$, $H_{crit}=5{\cdot}99$) at the 0·05 level.

DISCUSSION AND CONCLUSIONS

Although some of these differences are significant at the 0·05 level, the wide spread of results evident from the 95 per cent confidence limits (Figure 5) suggests that, whichever technique for measuring roughness is adopted, great care needs to be exercised when sampling to ensure that sample sizes are sufficient to adequately account for population variance. The results also support the cautionary remarks of McCarroll (1991) on the application of these techniques as a method of relative dating.

One possible reason for the large spread of roughness measurements yielded by the techniques employed here is that an individual fan segment cannot be regarded as having a uniform age; owing to the temporally and spatially discrete nature of sediment deposition on fans (Beaty, 1970), different parts of the same segment may be of very different ages (Mills and Allison, 1995b), which is reflected in different amounts of clast weathering (Mills and Allison, 1995c)

Another possible reason for the high variance in the data is sediment transfer between the fan segments; erosion of the upper segment may lead to subsequent redeposition of clasts from the upper segment to the younger segments. Furthermore, boulders can simply roll from higher to lower segments due to gravity-driven processes, leading to the emplacement of older clasts among younger material on lower segments.

Although the three fan segments do not provide a sound basis for drawing any firm conclusions, all the measurements discussed here show a rapid rate of change between 0 and 5000 years, with a slower rate evident during the previous 45 000 years. This would support the assertion of Lowe and Walker (1997) that weathering rates are not constant, but decrease over time, at least when measured by the techniques employed here. A similar trend was noted with regard to pedogenic enrichment of iron oxide minerals on the same set of fan segments (White and Walden, 1997).

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